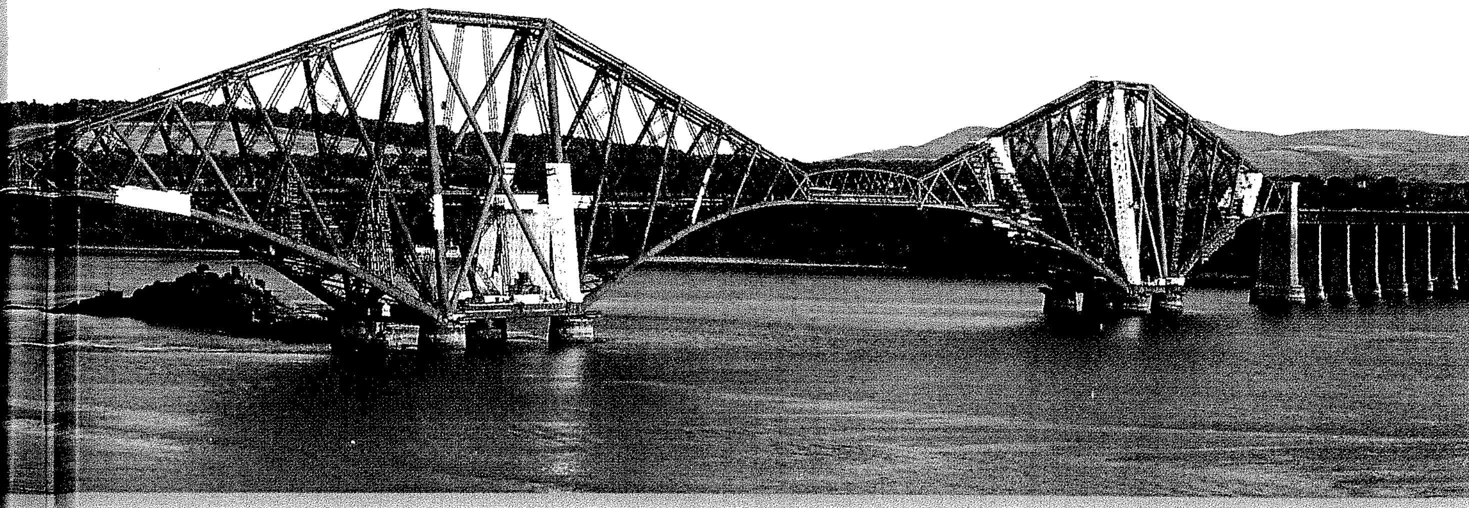

Sustainable Bridges

Assessment for Future Traffic Demands and Longer Lives

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Railway bridge defects and degradation mechanisms

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Development of cooperation within European Union stimulates intensive integration between all components of European transportation system. One of the important fields of integration is railway bridge engineering, a part of railway transportation system. Proposed classification of degradation mechanisms against their effects as bridge structure defects can be a basis for the unified assessment of bridge condition. Presented terminology and classifications elaborated in the European research project "Sustainable Bridges" can be useful in condition assessment by bridge inspectors as well as in knowledge-based computer tools supporting evaluation procedures in the advanced Bridge Management Systems. Identified relationships between degradation processes and defects can be used for optimization of bridge infrastructure maintenance and management.

1. INTRODUCTION

Problems connected with degradation processes of railway bridges are becoming more and more important issue in almost all European countries. During years of operation bridge structures are exposed to numerous degradation influences causing various types of defects and finally reducing bridge condition.

Bridge condition appraisal is based on the identification of structure defects and comparison of current and designed values of bridge technical and operational parameters. The applied methodologies of defects' classification and evaluation of their influence on bridge condition are fundamental for the assessment process. In each country bridge owners and administrators develop and use their own system, but at the same time international integration and cooperation within the European Union requires a harmonisation of the systems leading to comparable results of the condition assessment procedures (Bień et al., 2004).

Presented approach to classification of typical bridge defects and degradation mechanisms as well as proposed terminology should be considered as a part of international discussion. Common hierarchical classification of railway bridge defects is offered for basic structural materials (concrete, steel and masonry bridges) taking into account the material specific effects. On the other hand the degradation mechanisms causing defects are identified, defined and presented in three groups: chemical, physical and biological mechanisms. Relationships between the degradation mechanisms with the observed defects are shown for each of the considered structural materials. Presented terminology and classification systems can be used during the bridge inspections and also in knowledge-based computer tools supporting evaluation procedures in the advanced Bridge Management Systems.

Definitions of the basic terms used in this paper are as follows:

- *bridge condition* – general term describing current state of bridge structure,
- *defect* – each effect diminishing (reducing) bridge condition,
- *degradation mechanism* – a phenomenon causing defect (defects) to construction,
- *degradation process* – combination of degradation mechanisms.

2. CLASSIFICATION OF BRIDGE DEFECTS

General conception of hierarchical classification of the railway bridge defects (Figure 1) is based on the effect criterion – related to the results of the degradation mechanisms actions. The defects can be identified by visual methods as well as by means of various more advanced testing methods, mainly NDT techniques (Helmerich and Niederleithinger, 2006), applied during bridge inspections and presented in the Guideline for Condition Assessment and Inspection of Railway Bridges (Niederleithinger et al., 2006).

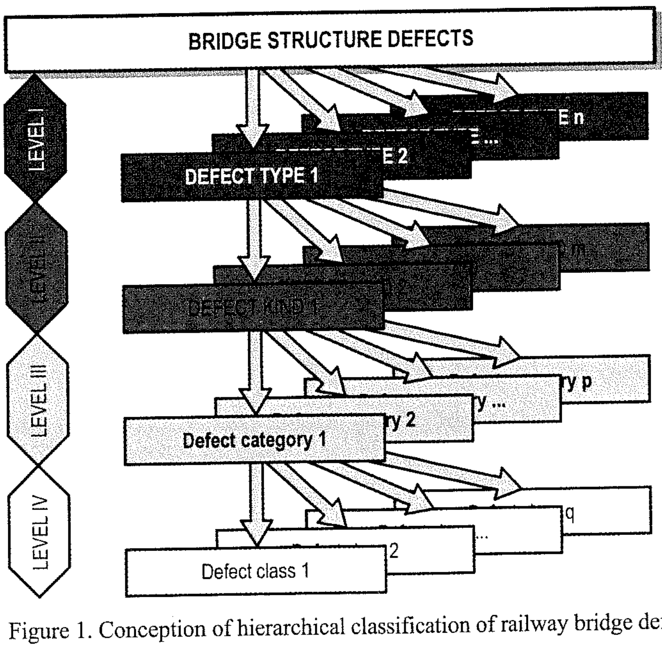
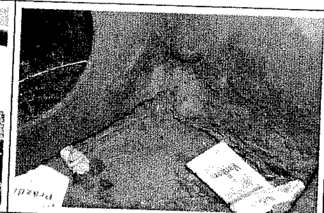
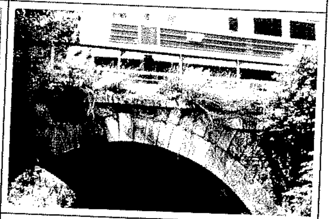
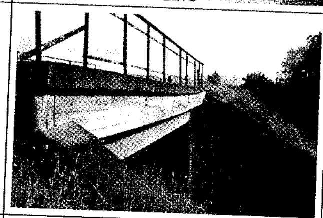
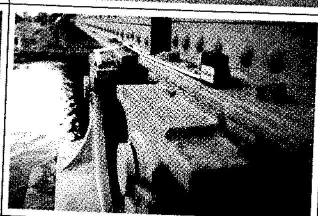
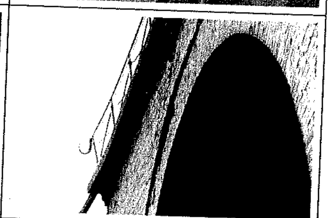
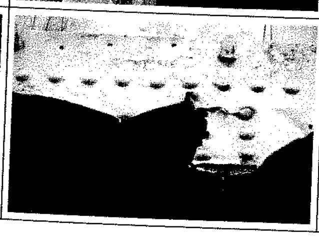
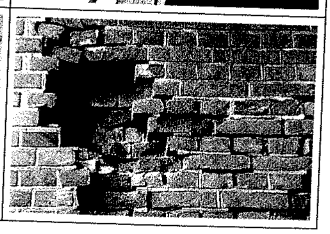


Figure 1. Conception of hierarchical classification of railway bridge defects

In the proposed classification six basic types of bridge defects are distinguished and are presented – in alphabetical order – in Table 1:

- *contamination* – appearance of any type of dirt, rubbish or not designed plant vegetation,
- *deformation* – geometry changes incompatible with the design, with changes of mutual distances of structure points,

Table 1. Basic types of railway bridge defects

Defect	Structural material		
	Concrete	Steel	Masonry
Contamination			
Deformation			
Deterioration			
Discontinuity			
Displacement			
Loss of material			

- *deterioration* – disadvantageous changes of physical and/or chemical structural features in relation to designed values,
- *discontinuity* – not designed break in the structure material continuity,
- *displacement* – change of the structure component (components) location incompatible with the design but without deformation of the structure, also restrictions in designed displacement capabilities,
- *loss of material* – decrease of designed amount of structure material.

The main defect types (level I in Figure 1) are the same for all structural materials (concrete, steel, masonry). Examples of main types of bridge defects are presented in Table 1.

Details of the hierarchical classification of the railway bridge defects for all basic types of the structural materials are presented in the next parts of the paper. The entire classification with photographical illustrations of the defects is presented in the Railway Bridge Defect Catalogue placed in Annex 2 to the Guideline (Niederleithinger et al., 2006).

3. DEGRADATION MECHANISMS

Taking into account nature of the degradation processes, the following main groups of degradation mechanisms can be distinguished:

- *chemical mechanisms* – causing degradation of bridge structures as a result of chemical reactions,
- *physical mechanisms* – diminishing condition of bridge structures by influence of physical phenomena,
- *biological mechanisms* – reducing condition of bridge structures by influence of biological phenomena.

Classification of basic degradation mechanisms identified in railway bridges is presented in Figure 2.

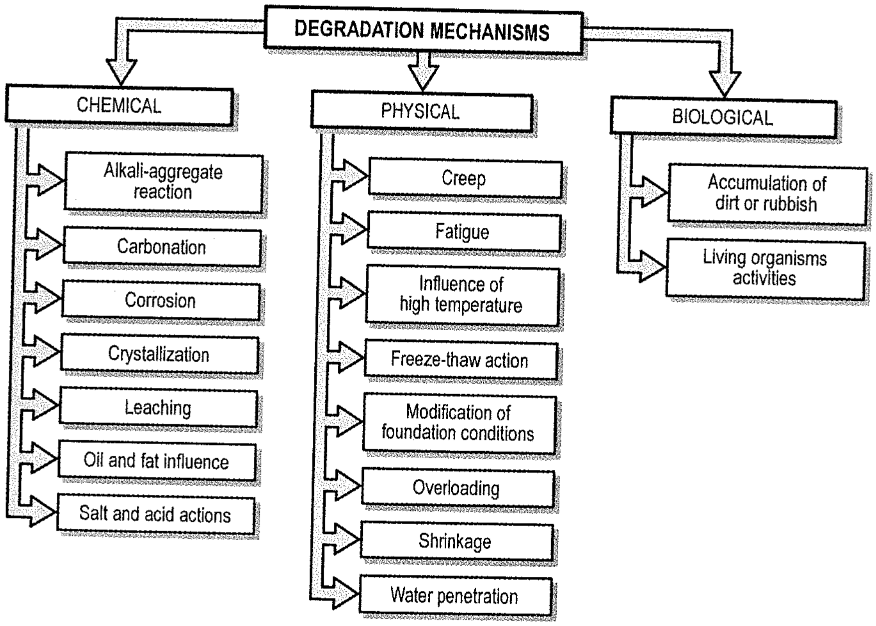


Figure 2. Degradation mechanisms of railway bridges

The most frequent chemical degradation mechanisms can be defined as follows (in alphabetical order):

- *alkali-aggregate reaction* – the mechanism caused by presence of aggregates and alkali, which leads to an expansive reaction and deterioration of concrete,
- *carbonation* – mechanism where carbon dioxide, from the atmosphere, enters to concrete and reacts with the hydroxides to form carbonates and water,
- *corrosion* – oxidation of metal causing deterioration and/or losses of material,
- *crystallization* – formation of crystal phase of salts in pores of structural material leading to defects due to volume increase of forming crystals,
- *leaching* – mechanism of the concrete components dissolving by water,
- *oil and fat influence* – reaction of oils and/or fats with the calcium hydroxide in concrete,
- *salt and acid actions* – chemical reactions mainly of compounds of sulphur, chlorine, nitrogen and magnesium with structural material.

In the group of physical mechanisms the following main processes causing degradation of concrete bridge can be distinguished:

- *creep* – inelastic strains caused by long-time load,
- *fatigue* – mechanism of sequential degradation of material caused by repeated cyclic loads,
- *influence of high temperature* – phenomenon caused by fire on or under the structure,
- *freeze-thaw action* – mechanisms caused by the expansion of pore water due to freezing,
- *modification of foundation conditions* – mechanism causing changes of structure geometry and redistribution of internal forces because of foundation movement,
- *overloading* – exceeding of the acceptable designed values of the bridge loads,
- *shrinkage* – mechanism caused by constraints of element deformation,
- *water penetration* – incompatible with design presence of water usually caused by inefficiency of drainage and/or waterproofing system.

Biological degradation mechanisms form the smallest but important group of processes diminishing condition of all railway bridges. The following main processes can be listed:

- *accumulation of dirt or rubbish* – mechanism of organic and non-organic contaminants gathering caused by environmental and/or human activities,
- *living organisms activity* – mechanism causing defects as a result of living organisms (bacteria, plants, animals) actions.

All described degradation mechanisms can be also classified taking into account duration of the degradation processes. The following groups can be distinguished:

- *incidental processes* – when the degradation process is very short (duration even below a second), e.g. overloading by collision or by earthquake,
- *short-time processes* – acting during hours or days, e.g. influence of extreme fire temperature, foundation displacement because of scour during flood,
- *long-time processes* – majority of considered degradation processes.

4. MATERIAL SPECIFIC DEFECTS AND DEGRADATION MECHANISMS

4.1. Concrete bridges

Relationships between the degradation mechanisms and the basic types of defects specific for concrete bridges, based on analysis of many practical cases, are presented in Table 2 as proposed by Maksymowicz et al. (2006). Shown results confirm complicated nature of degradation processes very often consisting of two or more interacting degradation mechanisms.

Table 2. Degradation mechanisms in relation to defects of concrete railway bridges

Degradation mechanisms / Defect type	Chemical							Physical								Biological	
	Alkali – Aggregate Reaction (AAR)	Carbonation	Corrosion	Crystallization	Leaching	Oil and fat influence	Salt and acid actions	Creep	Fatigue	Freeze-thaw action	Influence of high temperature	Modification of foundation conditions	Overloading	Shrinkage	Water penetration	Accumulation of dirt or rubbish	Living organisms activity
Contamination	■		■		■	■	■				■				■	■	■
Deformation				■				■			■	■	■	■			
Deterioration	■	■	■	■	■	■	■		■	■	■				■		■
Discontinuity			■	■					■	■	■	■	■	■			
Displacement												■	■			■	
Loss of material			■	■						■	■		■		■		■

Classification of typical defects identified in the bridge concrete structures are presented below in Table 3. Presented hierarchical system of classification enables selection of the required level of precision in defect identification and description.

The names of most of the defects presented in Table 3 (as well as in Table 5 and Table 7) can be understood literally, some of them, however, require definitions that are proposed as follows:

- *absorbability increase* – an increase in the material tendency to absorb water,
- *adhesion reduction* – a decrease in adhesion of protective coating to the structure element,
- *aggressive/neutral contamination* – inorganic dirtiness provoking/not provoking chemical or physical reaction of the structure,
- *calcium hydroxide reduction* – a decrease in the calcium hydroxide content in the structural material,
- *crack* – a discontinuity of the material perpendicular to the element surface, ranging a part of cross-section, the following crack orientations can be distinguished:
  - *irregular* – forming a network of discontinuities without a dominating direction,
  - *longitudinal* – parallel (±10°) to the element longitudinal axis,
  - *skew* – oriented 10–80° to the element longitudinal axis,
  - *transverse* – perpendicular (±10°) to the element longitudinal axis,
- *deflection* – a deformation of the structure element caused by bending forces, without the deformation of the element cross-section,
- *delamination* – a discontinuity of the structure material parallel to the element surface, including a ring separation in multi-ring arches,
- *embrittlement increase* – a decrease in material plasticity,
- *fading* – a loss of colour and/or brightness,
- *fracture* – a discontinuity of the material perpendicular to the element surface ranging the whole cross-section, dividing it into separate parts,
- *frost-resistance reduction* – a decrease in the structure material frost-resistance according to the designed value,
- *penetrating contamination* – organic contamination (e.g. plants, bacteria) penetrating deep into the structure,

Table 3. Hierarchical classification of defects of railway concrete bridges

CLASSIFICATION OF CONCRETE BRIDGE DEFECTS			
LEVEL I	LEVEL II	LEVEL III	LEVEL IV
Contamination	Concrete	Inorganic	Aggressive
			Neutral
		Organic	Penetrating
			Superficial
	Protection	Inorganic	Aggressive
			Neutral
		Organic	Penetrating
			Superficial
Deformation	Concrete	Deflection	
	Protection	Deflection	
Deterioration	Concrete	Modification of chemical features	Calcium hydoxide reduction
			pH factor reduction
			Salt concentration increase
		Modification of physical features	Absorbability increase
			Elastic modulus change
			Embrittlement increase
			Frost-resistance reduction
			Permeability increase
			Porosity increase
			Strength reduction
	Protection	Modification of chemical features	Calcium hydoxide reduction
			pH factor reduction
			Salt concentration increase
		Modification of physical features	Adhesion reduction
			Embrittlement increase
			Fading
			Frost-resistance reduction
			Permeability increase
			Porosity increase
	Reinforcement and prestressing system	Modification of physical features	Bond reduction
			Strength reduction
Discontinuity	Concrete	Crack	Irregular
			Longitudinal
			Skew
			Transverse
		Delamination	
		Fracture	
	Protection	Crack	
		Delamination	
		Fracture	
	Reinforcement and prestressing system	Crack	
		Fracture	
Displacement	Excessive	Rotation	
		Translation	
	Limited	Rotation	
		Translation	
Loss of material	Concrete		
	Protection		
	Reinforcement and prestressing system		

- *permeability increase* – an increase in the structure material vulnerability to passing through of water,
- *pH factor reduction* – an increase in carbon dioxide in concrete producing carbonates and the resulting pH value decrease,
- *rotation/translation* – rotational/translational displacement of the structure or its part without a deformation,
- *salt concentration increase* – an increase in the salt content according to the designed values, i.e. nitrogen compounds, chlorides, sulphates, magnesium or ammonium compounds,
- *slip* – a deformation of the structure element caused by shear forces, without the deformation of the element cross-section,
- *strength reduction* – a decrease in the structural material strength in respect of the designed values; especially compressive and shear strengths,
- *superficial contamination* – organic contamination located on the surface of the structure,
- *swell* – an increase in the volume of structural material.

4.2. Steel bridges

In the steel bridges like in the concrete bridge structures defining of the relationships between defects and degradation mechanisms is not simple, because one defect can be caused by few mechanisms and at the same time one mechanism can cause various defects of the structure. On the other hand competently defined connections between observed defects and degradation processes can be very useful as practical tool supporting bridge owners in creation of the optimal maintenance strategy. Attempt to description of the relationships between the main types of defects and basic degradation mechanisms occurring in the railway steel bridges is presented in Table 4 according to Bień and Jakubowski (2006).

Table 4. Degradation mechanisms in relation to defects of steel railway bridges

Degradation mechanism / Defect type	Chemical	Physical				Biological	
	Corrosion	Fatigue	Influence of high temperature	Modification of foundation conditions	Overloading	Accumulation of dirt or rubbish	Living organisms activities
Contamination	■		■			■	■
Deformation			■	■	■		
Deterioration	■	■	■				
Discontinuity		■	■	■	■		
Displacement				■	■	■	
Loss of material	■		■		■		

Classification of typical defects identified in the bridge steel structures are presented in Table 5. Definitions of the terms used in the classification are explained in chapter 4.1. Proposed four-level system of defect classification enables selection of the required precision in defect identification and classification.

Table 5. Hierarchical classification of defects of steel railway bridges

CLASSIFICATION OF STEEL BRIDGE DEFECTS			
LEVEL I	LEVEL II	LEVEL III	LEVEL IV
Contamination	Steel construction	Inorganic	Aggressive
			Neutral
		Organic	Penetrating
			Superficial
Deformation	Basic component	Deflection	
		Distortion	
		Torsion	
	Bolted/riveted connector	Deflection	
		Torsion	
	Welded connector	Deflection	
		Torsion	
Deterioration	Basic component	Modification of physical features	Hardness reduction
			Impact resistance reduction
			Strength reduction
	Bolted/riveted connector	Modification of physical features	Loosening
			Strength reduction
	Protection	Modification of physical features	Adhesion reduction
			Embrittlement increasing
			Fading
			Thickness reduction
	Welded connector	Modification of physical features	Strength reduction
Discontinuity	Basic component	Crack	Irregular
			Longitudinal
			Skew
			Transverse
		Delamination	
		Fracture	Irregular
			Longitudinal
			Skew
			Transverse
	Bolted/riveted connector	Crack	
		Fracture	
	Protection	Crack	
		Delamination	
		Fracture	
	Welded connector	Crack	Longitudinal
			Transverse
		Fracture	Longitudinal
			Transverse
Displacement	Excessive	Rotation	
		Translation	
	Limited	Rotation	
		Translation	
Loss of material	Basic component		
	Bolted/ riveted connector		
	Protection		
	Welded connector		

4.3. Masonry bridges

Identification of degradation mechanisms and processes occurring in masonry bridges is complicated because of complex nature of the structures. Composite action of bricks or stones, joints and backfill requires very precise analysis of degradation phenomena.

Usually there is no simple way of defining the relationships between defects and degradation mechanisms, because almost each defect can be caused by a few mechanisms or their combination. The most frequent relationships between the main types of defects and basic degradation mechanisms – based on the analysis of many practical cases – are presented in Table 6 according to Bień and Kamiński (2007).

Table 6. Degradation mechanisms in relation to defects of masonry railway bridges

Degradation mechanisms / Defect type	Chemical				Physical							Biological	
	Carbonation	Crystallization	Leaching	Salt and acid actions	Fatigue	Freeze-thaw action	Influence of high temperature	Modification of foundation conditions	Overloading	Shrinkage	Water penetration	Accumulation of dirt or rubbish	Living organisms activity
Contamination			■	■			■				■	■	■
Deformation		■		■		■	■	■	■	■			■
Deterioration	■	■	■	■	■	■	■				■		
Discontinuity		■			■	■	■	■	■	■			■
Displacement								■	■				
Loss of material		■				■	■		■		■		■

The detailed classification including all types of masonry bridge defects is shown in Table 7. For all main types of defects – except displacement – at the second level of the

Table 7. Hierarchical classification of defects of masonry railway bridges

CLASSIFICATION OF MASONRY BRIDGE DEFECTS			
LEVEL I	LEVEL II	LEVEL III	LEVEL IV
Contamination	Backfill	Inorganic	Aggressive
			Neutral
		Organic	Penetrating
			Superficial
	Masonry	Inorganic	Aggressive
			Neutral
		Organic	Penetrating
			Superficial
	Protection	Inorganic	Aggressive
			Neutral
		Organic	Penetrating
			Superficial
Deformation	Backfill	Deflection	
	Masonry	Deflection	
		Slip	
		Swell	
	Protection	Deflection	

CLASSIFICATION OF MASONRY BRIDGE DEFECTS (CONT.)			
LEVEL I	LEVEL II	LEVEL III	LEVEL IV
Deterioration	Backfill	Modification of physical features	
	Brick/stone	Modification of chemical features	Calcium hydroxide reduction
			pH factor reduction
			Salt concentration increase
		Modification of physical features	Absorbability increase
			Elastic modulus change
			Embrittlement increase
			Frost-resistance reduction
			Permeability increase
			Porosity increase
			Strength reduction
	Joint	Modification of chemical features	Calcium hydroxide reduction
			pH factor reduction
			Salt concentration increase
		Modification of physical features	Absorbability increase
			Elastic modulus change
			Embrittlement increase
			Frost-resistance reduction
			Permeability increase
			Porosity increase
			Strength reduction
	Protection	Modification of chemical features	Calcium hydroxide reduction
			pH factor reduction
			Salt concentration increase
		Modification of physical features	Absorbability increase
			Adhesion reduction
			Embrittlement increase
			Fading
			Frost-resistance reduction
			Permeability increase
			Porosity increase
Discontinuity	Masonry	Crack	Irregular
			Longitudinal
			Skew
			Transverse
		Delamination	
		Fracture	Irregular
			Longitudinal
			Skew
			Transverse
	Protection	Crack	
		Delamination	
		Fracture	
Displacement	Excessive	Rotation	
		Translation	
Loss of material	Backfill		
	Brick/stone		
	Joint		
	Protection		

classification, structure components afflicted with a defect are indicated. Detailed sub-types of the masonry bridge defects are distinguished on the lowest level of the presented classification. Definitions of the terms used in the classification are explained in chapter 4.1.

5. CONCLUSIONS

Presented classifications of bridge defects and degradation mechanisms together with the testing methods described in the Guideline (Niederleithinger et al., 2006) create a basis for a consistent identification and description of the railway bridge defects as well as for comparable assessment of their condition, e.g. (Bień et al., 2004; Bień and Kamiński, 2006). Defined relationships between degradation mechanisms and defects should help in optimisation of the maintenance strategies and in reliable foresight of the bridge infrastructure lifetime.

Presented solutions can be considered as a part of European discussion concerning common methodology of advanced bridge condition assessment and forecasting.

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